BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

869 03070

SUBJECT: Astronomy in Space
Case 105-3

DATE: March 20, 1969

FROM: D. B. Wood

ABSTRACT

The three most important reasons to establish space-based astronomical observatories are, in priority order

1. accessibility of new wavelength regions,
2. spatial resolution capability, and
3. non-varying background.

Increased spatial resolution is a double-edged benefit:

1. for the direct application of high resolving power to see small detail and resolve with small angular extent;

2. for the indirect effect of increasing the ability of the telescope to see fainter objects by compressing more photons into a smaller image.

The performance capability of a large space telescope is described in terms of field of view and resolution. System requirements to obtain high resolution include

1. mirror surface accuracy
2. mirror alignment
3. pointing stability
4. thermal control.

This memorandum spells out some specific areas of scientific interest which will profit from space-based observatories.

(NASA-CR-103955) ASTRONOMY IN SPACE (Bellcomm, Inc.) 19 p N79-72111

Unclas
00/15 11490

FF No. 602(A)
19 (PAGES) (THRU) none (CODE)
[redacted] (NASA [redacted] R TMX [redacted]) [redacted] (CATEGORY)
AV[redacted] NASA RESEA[redacted] CENTERS ONLY

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 03070

SUBJECT: Astronomy in Space
Case 105-3

DATE: March 20, 1969

FROM: D. B. Wood

MEMORANDUM FOR FILE

I. INTRODUCTION

This memorandum is based in part on notes prepared for an oral presentation given on January 30 to Bellcomm management as part of an astronomy seminar. The scientific reasons for doing astronomy from space have been described by many authors, and the Bibliography includes some of these.

There are three extremely important reasons to establish space-based observatories. In priority order these are

1. accessibility of new wavelength regions
2. spatial resolution capability, and
3. non-varying background.

In addition, there are a number of other benefits to astronomy offered by space, such as:

1. continuous uninterrupted viewing (from other than low earth orbit) and

2. the ability to build very large structures much more easily than on earth under 1-g environment.

II. ACCESSIBILITY OF NEW WAVELENGTH REGIONS

Figure 1 displays 20 decades of the electromagnetic spectrum. We must study all of thsse energy regions if we hope to understand the physical processes which occur in the universe. Particularly, we must investigate the entire electromagnetic spectrum to learn of the physical processes occurring in stars, interstellar space, and the cataclysmic events involved in the birth and death of stars and galaxies. In this figure we see that from the earth we are limited to only five or six of the 20 decades of the spectrum that will be of interest and available from space.

Some specific examples of what we can learn from these new spectral regions are given below.

1. Normal stars radiate in an approximate blackbody manner, so by the Wein law, the wavelength at which the greatest energy is emitted is given by

$$\lambda^* = 0.29/T.$$

For the sun, where T = 6000°K, λ^* is about 4.8×10^{-5} cm or 4800 Å. For a star with a temperature of 10,000°K (a star of spectral type AO) the wavelength is 2900 Å, which is shortward of the atmospheric window. Hence from the surface of the earth we cannot see the greatest portion of the energy put out by stars earlier than spectral type AO. These very hot stars expend energy at a very high rate, evolve quickly, and generally are particularly interesting and informative objects to study. The astrophysical processes in their atmospheres are quite different from the sun. Above 10,000°K most Hydrogen is ionized, the atmosphere consists mostly of hydrogen ions and electrons, and the electron pressure is very high.

2. Among the most abundant and important elements in the universe are Hydrogen, Helium, Carbon, Nitrogen and Oxygen. Determination of these abundances (or the abundances of any elements) is much more uncertain when we can only observe excited state transitions. The resonance transitions (to the lowest energy states) for these elements lie in the ultraviolet. Boron and Beryllium are important elements since they are formed in the process of nucleogenesis as the stars generate their energy by the conversion of hydrogen into helium, and their resonance lines lie in the UV. These and other examples of lines of particular interest are listed in Table I. These UV absorption lines, important for studies of the relationship between stellar evolution and the abundance of the elements, would be observable in even very cool stars.

Many of these same lines, plus some others (e.g. H_2 at 1108 and 1008 Å) would be important for determining the composition of interstellar matter. Matter between stars and between galaxies may account for well over half the mass of the universe, so it is very important.

Emission nebulae, particularly planetary nebulae, are in a highly excited state, but at a very low density. The forbidden emission lines which we can observe there allow as to determine constants of atomic physics for ions which cannot be studied in the laboratory. Examples are

[N V]	1240 Å
[N IV]	1488
[C IV]	1550
[C III]	1909
[Mg II]	2800

Molecules of astrophysical interest (such as H_2O, CH_4, NH_3, TiO, CH, NH, OH, C_2) have important lines in the UV and in the IR which cannot be observed from the earth.

3. Some of the most exciting astronomical discoveries have recently been made not in the usual visual spectral region. Quasars and pulsars were discovered by radio astronomers. Stars which radiate almost all of their energy in the x-ray region have been discovered from space. There is evidence that there must be a class of objects which radiates almost all of their energy in the sub-millimeter region, which can only be observed from space. Plasma oscillations below 30 MHz can only be observed from space, and vast amounts of energy may be involved in such oscillations.

III. OPTICAL RESOLUTION CAPABILITY

Due to the turbulence in the earth's atmosphere, observations made from the surface of the earth are typically limited to an angular resolution of about 2 arcsec. Under ideal conditions, for a very short period of time, resolution of 1/2 arcsec can be obtained. In space, resolution is limited only by the capability of the instrument itself. Resolution as a function of wavelength and aperture is shown in Figure 2. This figure also shows, for example, that the largest apparent stellar diameter is about .04 arcsec.

There are two basic reasons for striving toward the maximum possible resolution:

1. for the direct application of high resolving power to see small detail or resolve apparently small objects;

2. for the indirect effect of increasing the telescope's ability to see fainter objects by packing more photons into a smaller image.

A. High Resolution

Scientifically, we would like high resolution to learn about the following general areas:

1. Galactic Nebulae

We can learn a great deal about low density shock phenomena by resolving fine structure in planetary nebulae, the Crab Nebula, and other bright nebula. In certain turbulent regions, such as in Orion and Monoceros, we should be able to resolve proto stars - stars being born.

2. Stars

With high resolution we can separate close binary stars and learn more about the nature of individual stars (mass, temperature, density), and even resolve the actual disks of some supergiant stars such as Betelguese and Mira. We can learn much about stellar evolutionary processes and particularly about mass loss with high resolution studies of stellar shells (T Tauri stars, OB stars, and supergiants).

3. Galaxies

Much can be learned about galactic evolution by being able to resolve detail at the greatest possible distance. Because of the time it takes light to reach us, the farther we look into space, the farther back we look into time. If we can resolve spiral structure, stellar associations, ionized hydrogen (H II) regions and individual bright stars we can learn more about how the local galaxies must have looked long ago. Crucial to studying galaxies and cosmological problems is the distance scale of the universe. Cepheid (pulsating) variable stars and H II regions in galaxies are used as "standard sources" to determine galactic distances. Higher resolution allows us to push our calibration of distance farther into space. Are quasars extra-galactic? Perhaps actual resolution of their size or even structure can answer this question.

4. Edge of the Universe

Resolution of actual angular extent of galaxies at the "edge of the universe" can answer the cosmological problem of whether the universe is open or closed, for in the latter case the most distant galaxies would appear larger than galaxies less distant.

5. Solar System

Naturally we desire the best resolution possible to study surface details and atmospheric structure on the nearer planets and their moons as well as comets. Apparently smaller objects, such as Pluto and smaller moons could be resolved adequately to measure their size. (The diameter of Pluto is unknown.) Solar astronomers, in order to understand the physical processes in the sun, desire the best possible resolution of solar granulation (surface convective cells), coronal streamers (fine structure in the corona), and solar flares.

B. Photon Gathering Power

The collecting area of the telescope, and thus the number of photons it can intercept, varies as the square of the aperture. The area of the image into which these are compressed varies, from the Rayleigh formula, inversely with the square of the aperture. Hence the photon density in the image, number/area, increases as the fourth power of the aperture:

$$\frac{\text{number}}{\text{area}} \propto \frac{(\text{aperture})^2}{(\text{wavelength}/_{\text{aperture}})^2} \propto (\text{aperture})^4$$

On the earth, since image area is governed by the atmosphere, a 2-meter telescope can only perceive 4 times fainter objects than a 1-meter telescope. However, a space-based 2-meter telescope can perceive 16 times fainter objects than a space-based 1-meter telescope. The particular nature of the instrumentation at the focus will determine ultimately the ability of the space telescope to utilize this potential $(\text{aperture})^4$ gain.

This possibility of observing extremely faint objects will allow us to

1. discover intrinsically faint objects in the solar neighborhood (nearby red dwarfs, white dwarfs, or possible "dead" stars),

2. study interstellar matter over extremely long path lengths,

3. study stars and matter in the spherical halo around our galaxy (these objects are apparently quite different from the "disk" population),

4. study individual stars in nearby galaxies and dwarf galaxies, and

5. detect extremely remote galaxies.

C. Performance Capability

1. Field of View

As aperture increases and the telescope becomes more and more capable of resolving fine detail and detecting faint objects, the required field of view of the telescope becomes smaller. Table II indicates the field of view requirements for various astronomical targets. In many cases the resolution required for a tremendous gain in scientific knowledge is about 0.1 arcsec. Figure 3 shows the field of view required versus resolution, with the possible capabilities of various telescopes indicated. It is seen that three telescope types: a 3-meter Cassegrain, a 1-meter Ritchey-Chretien (for wider angle), and a high resolution Schmidt (for even wider angle) can satisfy the present performance requirements.

The Palomar Sky Survey may represent the greatest density of data ever collected in terms of field imaging. The photographs each cover an area 6.6 degrees on a side, with a resolution of about 2 arcsec. Exclusive of intensity information, each plate thus contains some 1.4×10^8 bits. If a space telescope is capable of resolution to .04 arcsec (3-meter aperture), then the same density of data will be contained in a field of 7.2 arcmin as in the Palomar field of 6.6 degrees.

2. Requirements on System to Obtain High Resolution

Detailed analysis of the allowable tolerances is a whole subject in itself. Some of the more important aspects of the problem will be outlined here. The term "diffraction limited" is ambiguous, and should only be used if one is aware of all the factors which limit resolving power.

a. Surface accuracy of mirrors

Figure 4 shows the required rms surface accuracy to concentrate a given fraction of the light into the area of the Rayleigh disk for a two mirror system (for a one-mirror, or prime focus telescope, the surface could have twice the inaccuracy). Optical systems are generally considered "poor" if the central diffraction maximum contains less than 80% of what a perfect system would contain. This perfect system with no surface errors, can only concentrate 84% of the light in the

Rayleigh disk, so .8 in this figure really means that only 67% of the reflected light is in the central maximum.

The Stratoscope II mirror (36 inch diameter) was figured to an rms surface accuracy of ±100 Å, which is the highest accuracy yet obtained. It is reasonable with current technology and lots of care and time to get to about ±60 Å. Other techniques (e.g. ion bombardment, laser etching, etc.) might allow higher surface accuracy, but ±5-10 Å is probably the ultimate limit, because that represents the size of the molecules which make up the mirror surface.

Two important factors which determine our capability to obtain high resolution with an optical system are the amount of light in the Rayleigh disk and the angular extent of that disk. That is, we wish to put the greatest fraction of light into a small disk.

If we define a "resolution merit figure" as the fraction of light in the Rayleigh disk divided by the diameter of that disk, we have one possible way of evaluating the capability of a telescope to obtain high resolution. Figure 5 shows the resolution merit figure versus wavelength. Since the size of the image varies directly with wavelength, a perfect system approaches infinite resolution merit at zero wavelength. Practically, however, it is limited by the surface inaccuracies, which are relatively worse at short wavelength. We see from this figure the relative advantages of large apertures and high surface accuracies. The best resolution merit figure for a given mirror system occurs in the ultraviolet, not in the visual. Two important factors which are necessary to relate Figure 5 to a practical system are the mirror reflectivity and sensor (film, TV, etc.) performance, both of which are wavelength dependent.

More complete specification of resolution capability is obtained, with Modulation Transfer Functions (MTF), which specify intensity at all spatial frequencies at any point in the image plane.

b. Mirror alignment

In order to obtain the resolution of which the mirrors are intrinsically capable (as described above), they must maintain accurate alignment with each other. Table III gives approximate alignment tolerances of the secondary mirror with respect to the primary mirror. The table shows the great utility of an active optical element, which relaxes the mirror alignment tolerances with respect to the optic axis by between one and two orders of magnitude. These numbers are based on simple considerations of geometrical ray traces and diffraction theory. It is expected that a detailed MTF analysis might well tighten these tolerances.

c. Pointing stability

If the telescope mirrors are figured and aligned properly, they must further be accurately pointed in space. If the image wanders in the focal plane due to telescope "jitter", then the image is smeared and is no longer "diffraction limited". Depending on the performance we desire, the pointing stability should be 4x to 10x better than the resolution capability of the telescope. This required pointing stability which would be .01 to .004 arcsec for a 3-meter telescope, would most likely be achieved not by controlling the entire telescope (hence the primary mirror) but by using a low mass moving optical element to follow any image motion to the required accuracy. From Table III we saw the advantage of such an active optical element in reducing the mechanical alignment tolerances.

d. Thermal control

Obviously all the above are strongly influenced by any thermal gradients and transients in the telescope. Extremely precise thermal control is necessary to maintain the mirror figure and alignment. The exact thermal tolerances depend on the materials used, but are generally less than one degree for the mirrors. Slow temperature variations or thermal gradients in the structure may be considerably larger if there is an active optical element to compensate for any small structural warpages.

IV. SKY BACKGROUND

The sky background as seen from the earth in optical wavelengths is produced by

1. airglow atomic and discrete molecular emission lines,
2. airglow continuum, including cosmic ray produced Cerenkov radiation,
3. Scattered light (cities, stars, moon, etc.),
4. Zodiacal light and Gegenschein, and
5. Unresolvable background stars and galaxies.

By going into space, we can avoid the first three of these sources of background. This is particularly nice because these three sources are all strongly time and direction dependent. Thus the AC component of the background is removed.

The largest background in space is produced by the zodiacal light. The minimum background at the ecliptic poles, is about 40 tenth magnitude stars per square degree, or 23.8 magnitudes. This is about .3 magnitude less than a "dark" sky on earth.

The lack of a variable background will allow

1. observations of fainter stars
2. detection of extended objects
3. highly accurate photometric measures (to ±.0001 mag. or better)
4. time resolution of variable phenomena, particular variable stars such as eclipsing stars, cepheid and RR Lyr type variables, pulsars, and nova.

D B Wood

1015-DBW-caw

D. B. Wood

Attachments
Bibliography
Tables I-III
Figures 1-5

BIBLIOGRAPHY

Code, A. D., "Stellar Astronomy from a Space Vehicle," Astron. Journal, Vol. 65, June 1960, pp. 278-284.

Danielson, R. E., "Large Telescopes in Orbit," Internat. Science and Technology, No. 67, July 1967, pp. 54-64.

Goldberg, L. and E. R. Dyer, Jr., "The Sun" (Chap. 17) and "Galactic and Extragalactic Astronomy" (Chap. 18) in Science in Space, ed. L. V. Berkner and H. Odishaw, McGraw Hill, 1961.

Kopal, Z., "Tasks for the Manned Orbital Telescope," Astronautics and Aeronautics, Vol. 3, No. 12, December 1965, pp. 16-21.

Spitzer, L. Jr., "Astronomical Research with the Large Space Telescope," Science, Vol. 161, July 1968, pp. 225-229.

TABLE I

SOME ULTRAVIOLET LINES OF ASTROPHYSICAL INTEREST

ELEMENT / ION	WAVELENGTH (Å)
H I	1216
Ne I	584
Ne II	304
C I	1561
C II	1335
C IV	1549
N I	1200
N II	1085
N V	1240
O I	1302
O VI	1035
Be I	2349
B I	2090
B II	1362
B III	2067
Mg I	2852
Mg II	2800
Si I	2060
Si II	1533
S I	1807
S II	1255
Al I	2800
Al II	1670

TABLE II

FIELD OF VIEW REQUIRED TO OBSERVE MOST ASTRONOMICAL OBJECTS

FIELD	OBJECTS
$\leqslant 5''$	Individual stars; galaxies at the "edge" of the universe
$\leqslant 4'$	Globular clusters; planetary nebulae; planets; some emission nebulae; distant galaxies; solar active regions.
$\leqslant 30'$	Most galaxies; some clusters of galaxies; some galactic clusters and emission nebulae; w Centauri (nearest globular cluster); sun; moon
$\leqslant 5°$	Andromeda galaxy; Small Magellanic Cloud;* most galactic clusters; dark nebulae; emission nebulae; most clusters of galaxies
$\leqslant 10°$	Stellar associations; Large Magellanic Cloud;* galactic clusters; clusters of galaxies
$> 10°$	Virgo cluster (nearest cluster of galaxies); Milky Way; some large stellar associations

*The Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) are the nearest to ours.

TABLE III

TYPICAL ALIGNMENT TOLERANCES FOR AN f-30 CASSEGRAIN TELESCOPE

Motion of secondary	with an active optical element to follow any gross motion of whole image	without an active optical element
Rotation about vertex	1 arcmin	1 arcsec
Motion Perpendicular to optic axis	0.1 mm	.003 mm
Motion along optic axis	0.01 mm	0.01 mm

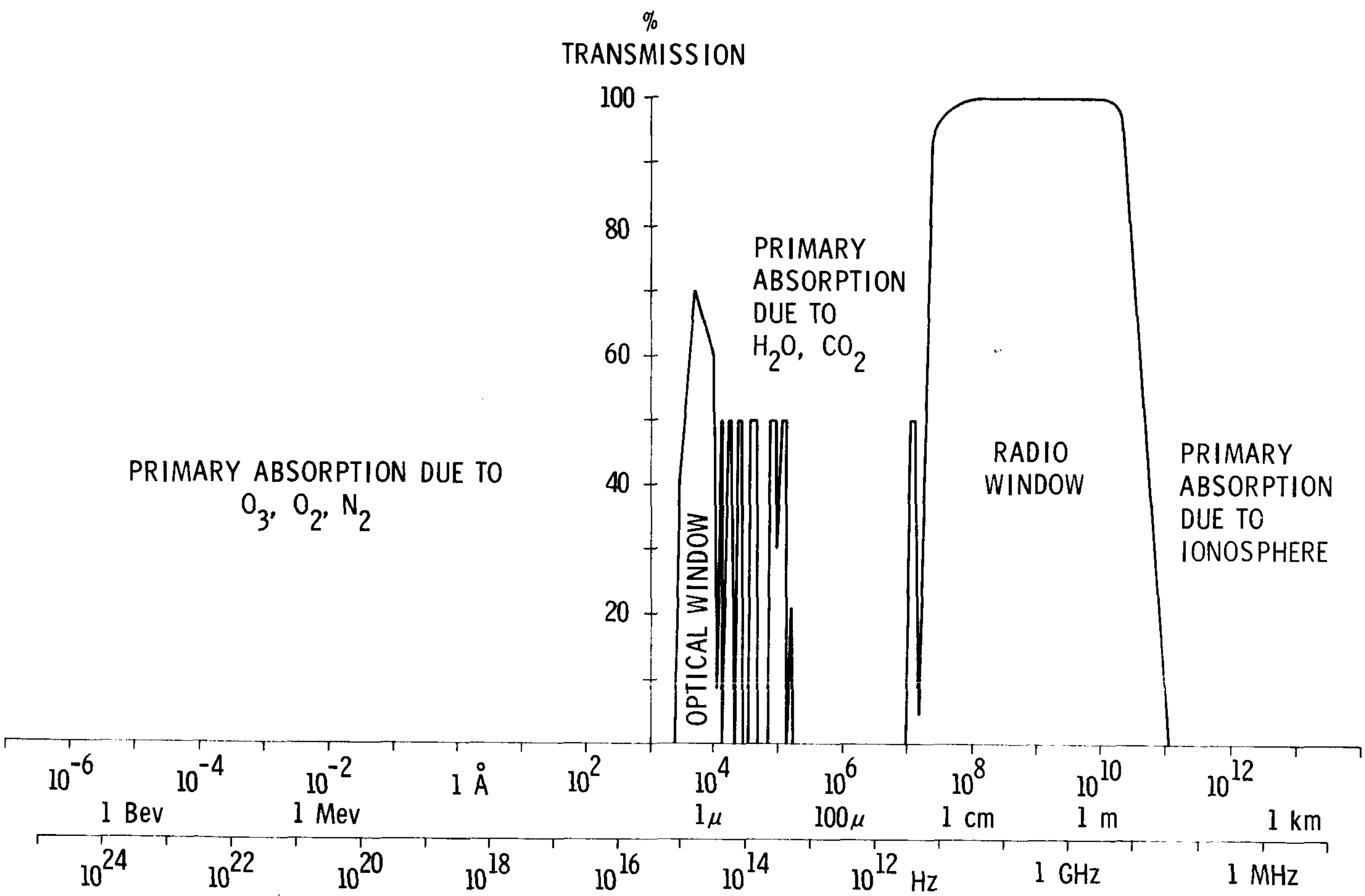

FIGURE 1 - ELECTROMAGNETIC SPECTRUM OF INTEREST IN ASTRONOMY

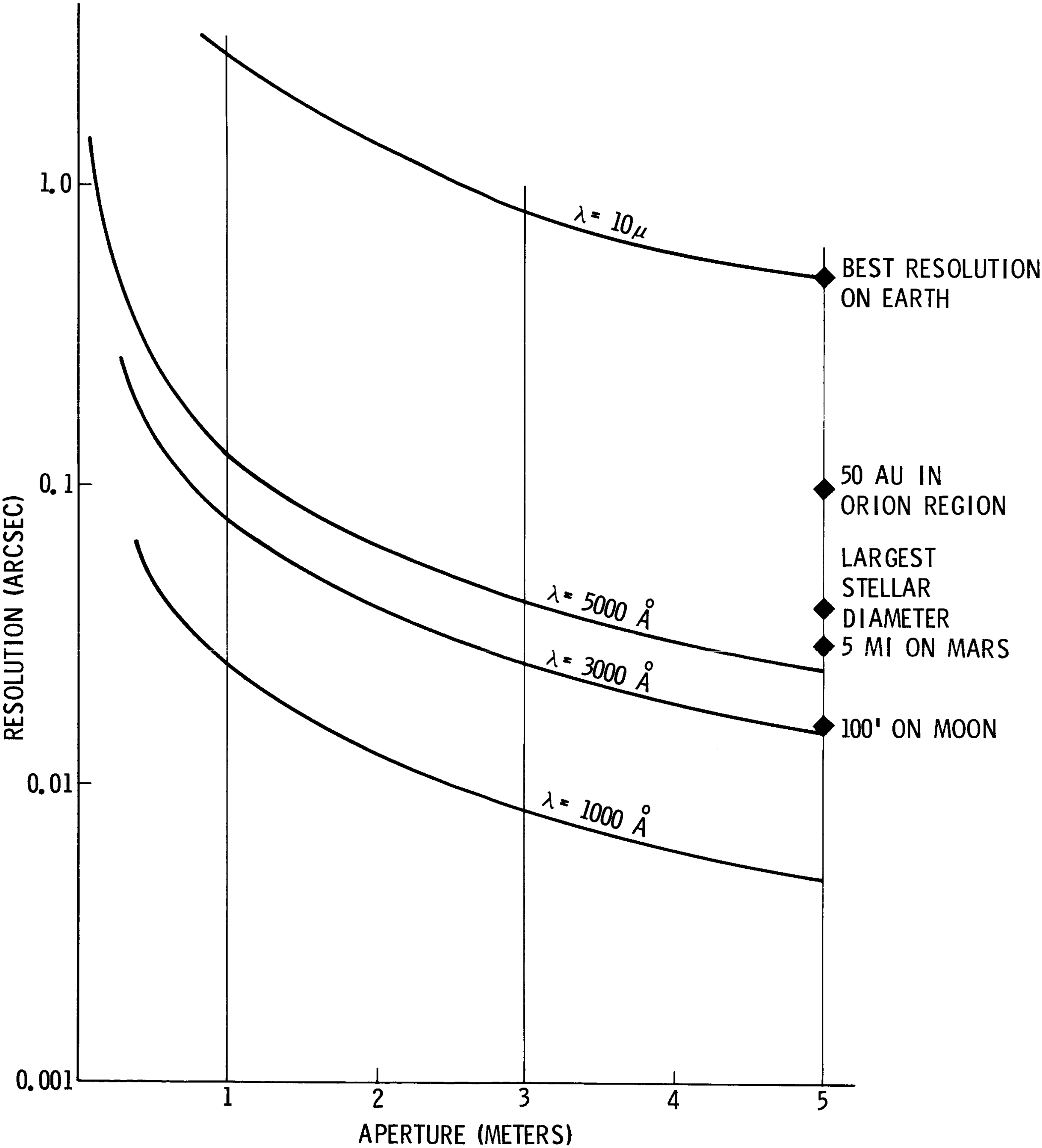

FIGURE 2 - TELESCOPE RESOLUTION

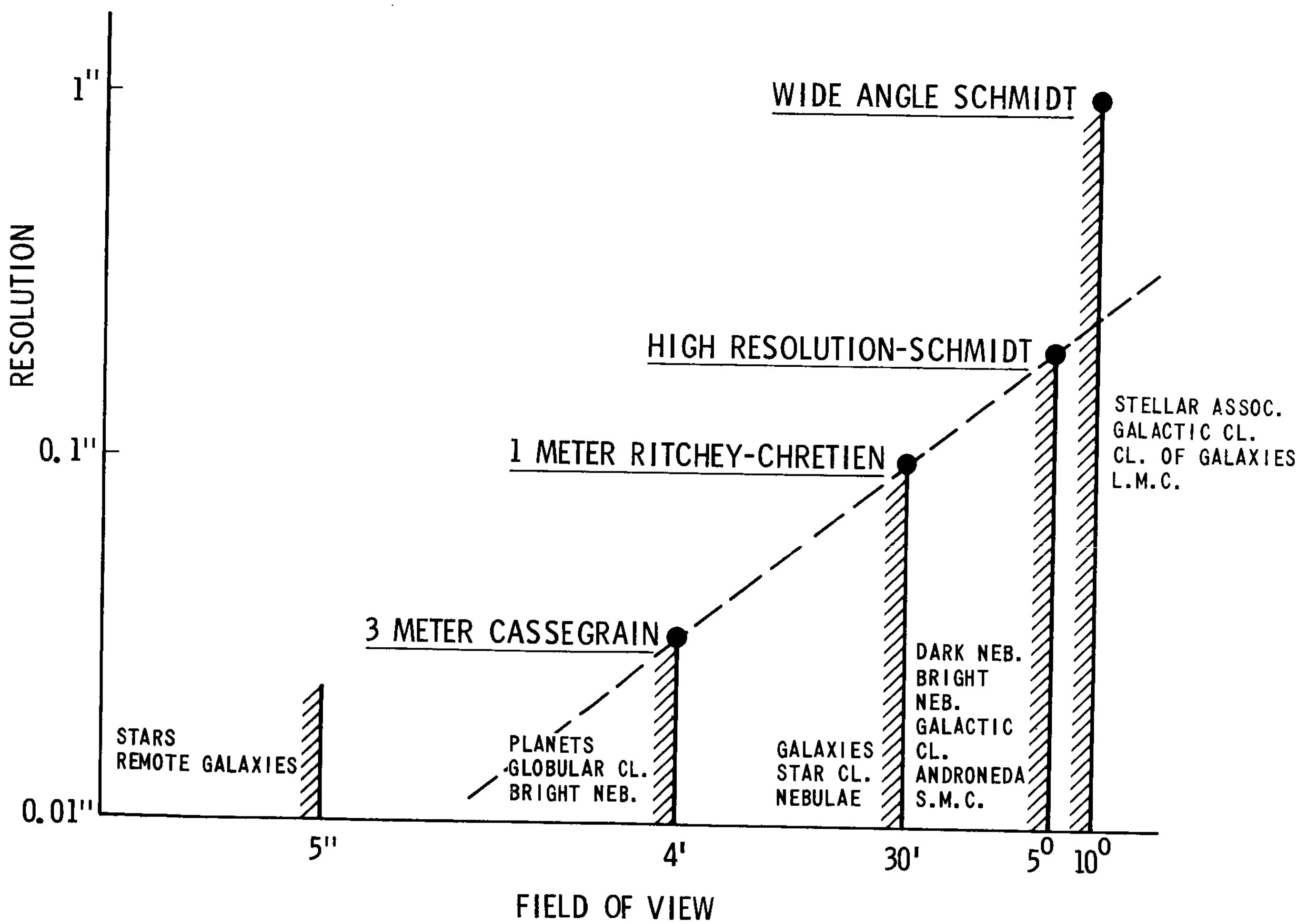

FIGURE 3 - FIELD OF VIEW REQUIREMENTS

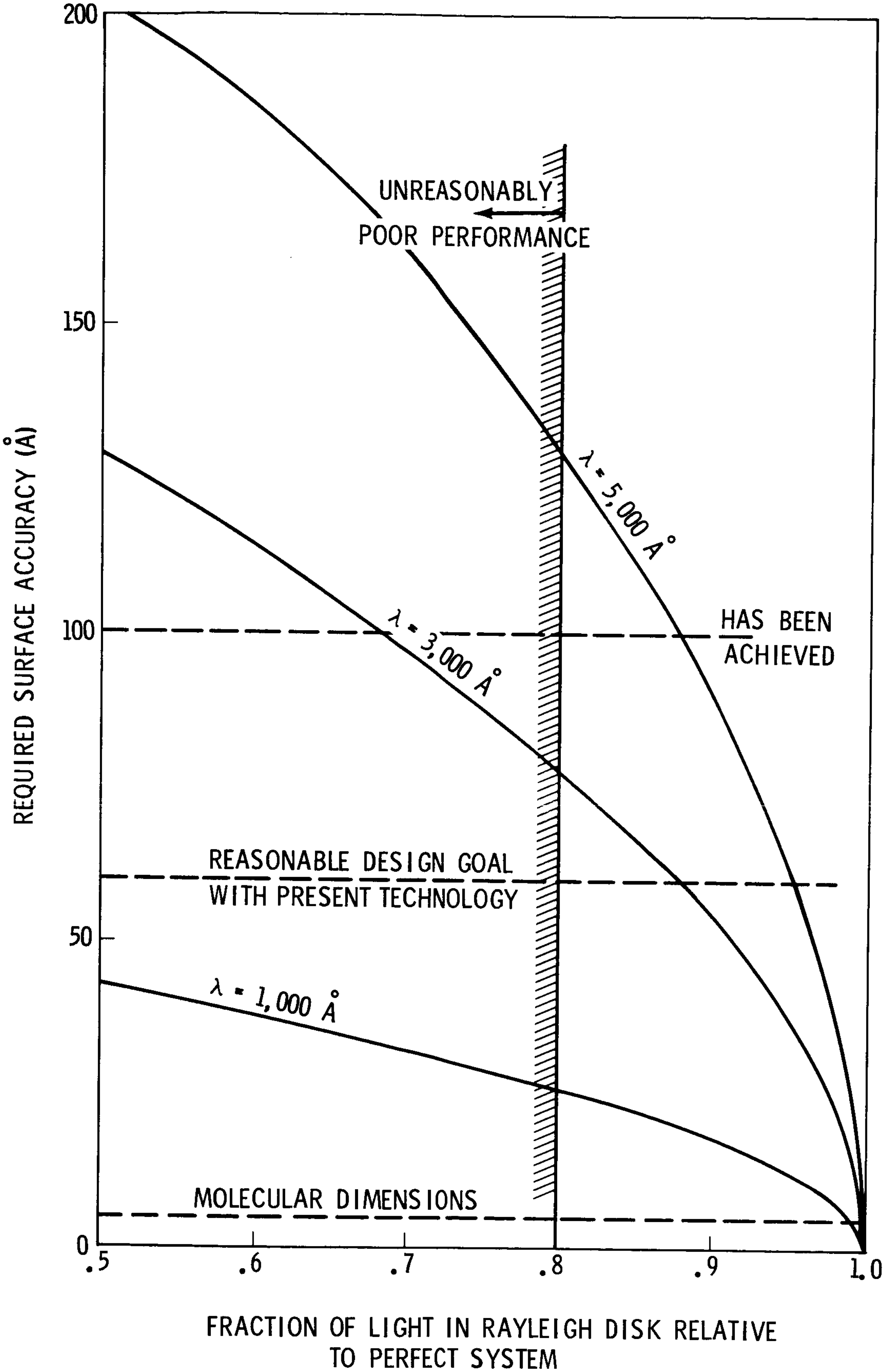

FIGURE 4 - MIRROR SURFACE ACCURACY

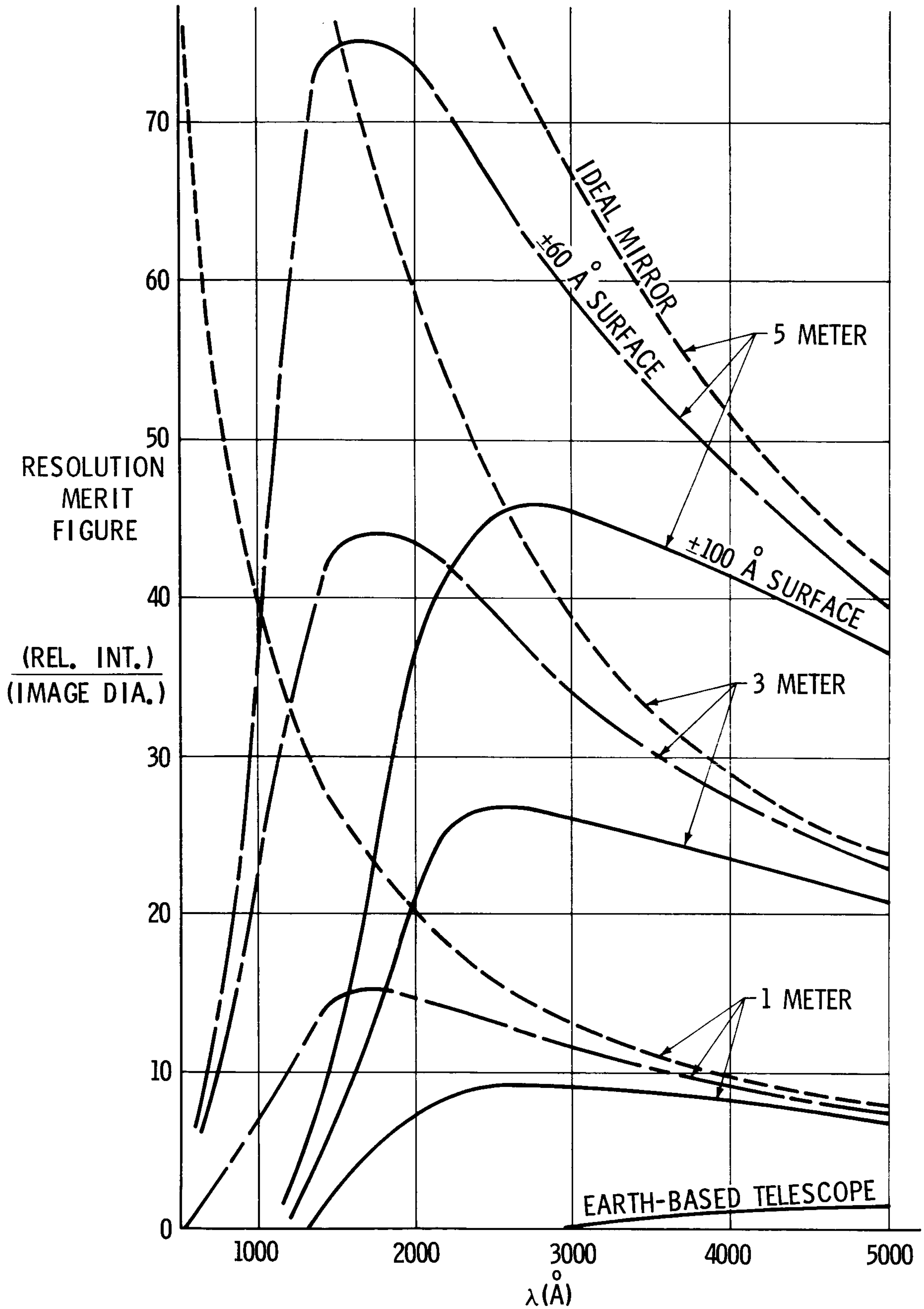

FIGURE 5 - RESOLUTION PERFORMANCE

BELLCOMM, INC.

Subject: Astronomy in Space
Case 105-3

From: D. B. Wood

Distribution List

NASA Headquarters

Messrs. W. O. Armstrong/MTX
C. D. Ashworth/SG
M. J. Aucremanne/SG
C. J. Donlan/MD-T
D. L. Forsythe/MLA
H. Glaser/SG
E. W. Hall/MTG
H. Hall/MTX
R. W. Johnson/MTX
T. A. Keegan/MA-2
R. L. Lohman/MTY
D. R. Lord/MTD
J. L. Mitchell/SG
M. W. Molloy/MAL
L. Roberts/OART-M (2)
A. D. Schnyer/MTV
H. J. Smith/SS
M. G. Waugh/MTP
J. W. Wild/MTE
Miss N. G. Roman/SG

Bellcomm, Inc.

Messrs. F. G. Allen
G. M. Anderson
D. J. Belz
A. P. Boysen, Jr.
J. O. Cappellari, Jr.
D. A. Chisholm
T. H. Crowe
C. L. Davis
D. A. DeGraaf
D. R. Hagner
P. L. Havenstein
N. W. Hinners
W. W. Hough
B. T. Howard
D. B. James
J. Kranton
H. S. London
K. E. Martersteck
W. I. McLaughlin
J. Z. Menard
G. T. Orrok
I. M. Ross
F. N. Schmidt
W. Strack
W. B. Thompson
J. W. Timko
R. L. Wagner
J. E. Waldo
All Members Division 101
All Members Division 102
Department 1024
Central File
Library